

DUST EXTINCTION BIAS IN THE COLUMN DENSITY DISTRIBUTION OF GAMMA-RAY BURSTS; HIGH COLUMN DENSITY, LOW REDSHIFT GRBS ARE MORE HEAVILY OBSCURED

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ABSTRACT

The afterglows of gamma-ray bursts (GRBs) have more soft X-ray absorption than expected from the foreground gas column in the Galaxy. While the redshift of the absorption can in general not be constrained from current X-ray observations, it has been assumed that the absorption is due to metals in the host galaxy of the GRB. The large sample of X-ray afterglows and redshifts now available allows the construction of statistically meaningful distributions of the metal column densities. We construct such a sample and show, as found in previous studies, that the typical absorbing column density (N_{Hx}) increases substantially with redshift, with few high column density objects found at low to moderate redshifts. We show, however, that when highly extinguished bursts are included in the sample, using redshifts from their host galaxies, high column density sources are also found at low to moderate redshift. We infer from individual objects in the sample and from observations of blazars, that the increase in column density with redshift is unlikely to be related to metals in the intergalactic medium or intervening absorbers. Instead we show that the origin of the apparent increase with redshift is primarily due to dust extinction bias: GRBs with high X-ray absorption column densities found at $z \lesssim 4$ typically have very high dust extinction column densities, while those found at the highest redshifts do not. It is unclear how such a strongly evolving N_{Hx}/A_V ratio would arise, and based on current data, remains a puzzle.

Subject headings: gamma-ray burst: general — early universe — dark ages, reionization, first stars — galaxies: ISM

1. INTRODUCTION

While it is now generally accepted that long-duration gamma-ray bursts (GRBs) primarily originate in the explosions of massive stars due to their association with type Ic supernovae, the precise nature of the progenitors and the environment in which the burst occurs are not known. Most progress to date has been made through afterglow observations; providing redshifts, emission mechanisms and information on the host galaxies. However the X-ray afterglows are still poorly understood. Indeed, one of the outstanding puzzles in understanding long GRBs is the nature and origin of the soft X-ray absorption observed in the majority of afterglows. Most GRB afterglows show evidence of absorption in the soft end of the X-ray spectrum significantly in excess of what is expected from the Galactic gas column. This has been known statistically from samples since the *BepoSAX* era (Galama & Wijers 2001), though first observed at high confidence in a single spectrum with *XMM-Newton* (Watson et al. 2002). It has generally been assumed from the beginning that the soft X-ray opacity is due to photoelectric absorption by the inner shells of the atoms in a column of metals – primarily O, Si, S, Fe, He – in the host galaxy of the GRB, in a fashion directly comparable to the X-ray absorption observed due to gas in the Galaxy. However, the absorption was quickly realised not to be directly analogous to Galactic soft X-ray absorption. The X-ray absorption in the Galaxy is strongly correlated with the dust and H I column densities (see Watson 2011, and references therein). However, for GRBs,

the correlation with dust extinction was not clear, and if it existed, was certainly at least an order of magnitude lower in dust-to-metals ratio compared to the local group (Zafar et al. 2011a; Schady et al. 2010). There was also no obvious correlation with the H I column densities (Watson et al. 2007; Campana et al. 2010; Schady et al. 2011). More recently a further puzzle was added. Campana et al. (2010) showed that the observed X-ray absorptions rose with redshift, with the highest column density objects ($\log N_{\text{Hx}} \sim 23$) appearing at the highest redshifts, and no comparably high column densities occurring at low redshifts ($\log N_{\text{Hx}} \lesssim 22$ at $z < 1.5$). This result was particularly puzzling since the X-ray absorption measures the total metal column density, and the gas metallicity is expected to decrease rather than increase to high redshift.

It was noted by Behar et al. (2011) that the *observed* opacity at low energies, while high at low redshift, tended toward an asymptotic value at $z \gtrsim 2$. This was interpreted as possible evidence for the detection of absorption by a diffuse, highly-ionised intergalactic medium (Behar et al. 2011). Such an interpretation has the virtue that it would solve the problems of the lack of correlation observed between the Ly α -determined H I column densities and the X-ray column densities in GRB afterglows, and the very low apparent dust-to-metals ratios.

Finally, a recent investigation of a largely redshift-complete sample of bright GRBs (Campana et al. 2012) found a statistically insignificant mild increase of X-ray absorption with redshift and interpreted it as due to increasing absorption by intervening systems in higher redshift GRBs.

In this paper we address the nature of the X-ray absorption in GRB afterglows; we investigate the apparently increasing absorption with redshift, the claim of a possible detection of the warm-hot intergalactic medium, and the role of dust extinction. In section 2 we detail the data used and our data analysis method. In section 3 we provide the results of our analysis. Section 4 contains a discussion on the interpretation of these results.

2. OBSERVATIONAL DATA AND METHODS

We analysed the XRT data from every long-duration burst observed by *Swift* up to November 2010. For each GRB in this set with a known redshift, we used the spectra produced by the auto-analysis of Evans et al. (2009) with the corresponding response files and fit a model consisting of a power-law absorbed by Galactic gas and gas at the redshift of the GRB to each dataset. We obtained redshifts for all bursts from the literature, primarily from Fynbo et al. (2009), Jakobsson et al. (2012), Krühler et al. (2012), and GCNs. This resulted in 175 GRBs. The data from windowed timing (WT) and photon counting (PC) modes were fit separately. The Galactic gas was modelled with an absorber fixed at a level set by the dust extinction in the direction of the GRB (Schlegel et al. 1998) with $N_{\text{H,MW}} = 2.2 \times 10^{21} A_V$, as suggested by Watson (2011). The method used to determine the Galactic column density of metals (whether using the neutral hydrogen or the dust as a tracer), does not appear to significantly affect the results as we obtain similar values for the excess absorption as previous authors where the GRBs analysed are in common (Campana et al. 2010). The absorption at the redshift of the GRB was allowed free to vary. The model used was `tbabs(ztbabs(pow))` in Xspec with metallicities from Anders & Grevesse (1989). We used the absorption model of Wilms et al. (2000) to fit the data as the atomic cross-sections are more accurate. We use the metallicity of Anders & Grevesse (1989) for ease of comparison with previous results, which generally use these abundances. It should be noted that while these abundances are significantly higher than the best estimates of the solar photosphere abundances (Asplund et al. 2009), they are likely a better estimate of the typical Galactic ISM abundance (Watson 2011). In any event, as noted above, we sidestep this metallicity conversion problem for the Galactic absorption simply by using the measured relationship between dust and X-ray absorption. However, it should be born in mind that the excess equivalent hydrogen column densities we report here are determined assuming an abundance approximately 50% higher than solar. Thus, for almost any GRB host these numbers are lower limits to the actual gas column density and if the real gas column is sought should be corrected for the probable metallicity of the GRB host galaxy. In this paper, we simply use the equivalent hydrogen column density as a proxy for the total metal column density. We do this for comparison with previous work, since this is what has been done by many authors before; and because we cannot determine individual metal column densities, the hydrogen proxy is the easiest one to deal with in a simple way.

The absorption in the X-ray afterglows of some GRBs appears to decrease as a function of time (e.g. Starling et al. 2005; Gendre et al. 2007; Campana et al. 2007). For this reason, where the WT and PC data gave statistically different values of the absorption, the later PC data gives us a conservative (low) value of the absorption. However, the WT data often has considerably higher signal. Therefore, where the

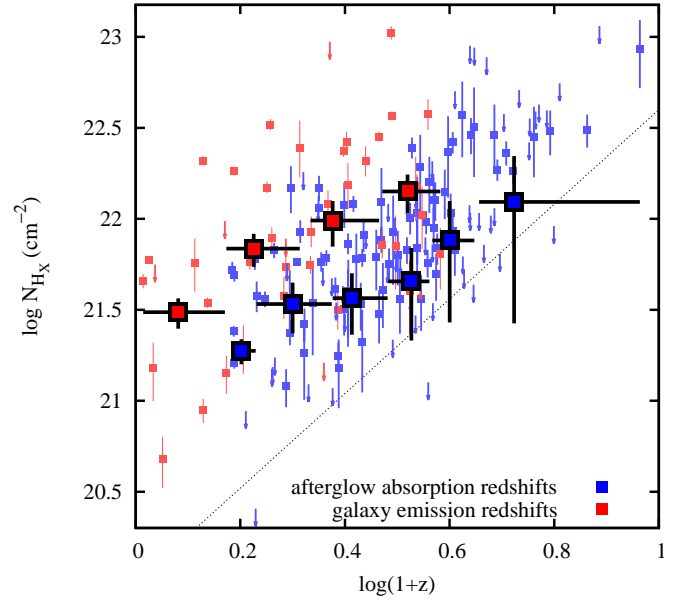


Figure 1. The X-ray absorption of GRB afterglows as a function of redshift. Overplotted in larger symbols is the mean absorption in a given redshift window taking into account upper limits. GRBs with redshifts obtained from absorption lines in the optical afterglow are plotted in blue. Those with redshifts obtained from host galaxy emission are plotted in red. The bias introduced due to dust extinction is clear in the systematically higher column densities in the emission redshift GRBs ($\Delta \log N_{\text{H}_X} = 0.31 \pm 0.08$). The host emission redshift sample still has lower absorption at low redshifts possibly due to significant remaining incompleteness in the sample, and there is no evidence for a more constant distribution of column densities than in the afterglow-selected sample. The dotted line marks a 10^{20} cm^{-2} absorber at $z=0$ evolved as $(1+z)^{2.5}$, showing the approximate detectability threshold for absorption as a function of redshift for a typical *Swift*-XRT GRB afterglow.

PC and WT mode data gave results consistent within 1σ (68% confidence), the value with the smallest uncertainty was used. Where the results were discrepant at $> 1\sigma$, the PC value was used. This procedure will be conservative in the sense that it will tend to lower values of N_{H_X} .

We determined extinction estimates for the GRB afterglows from the works of Zafar et al. (2011a), Greiner et al. (2011), Schady et al. (2010), and Kann et al. (2010) primarily. In cases where no explicit estimate of extinction could be found, we used the deepest limits from optical/NIR observations from the literature and the corresponding X-ray data, to determine values or limits on β_{XOX} (van der Horst et al. 2009; Jakobsson et al. 2004), where $\beta_{\text{XOX}} = \beta_X - \beta_{\text{OX}}$. From these data, we could then also derive limits on the restframe extinction: we use the theoretical and empirical determination that $\Delta\beta = 0.5$ (Zafar et al. 2011a; Sari et al. 1998), and that hence, $\beta_{\text{XOX}} \leq 0.5$. We then assumed an SMC extinction curve, found by all works to date to be most typical of the extinction for most GRB afterglows (Zafar et al. 2011a; Greiner et al. 2011; Schady et al. 2010; Kann et al. 2010), to determine a limit on the minimum extinction required to make the optical/NIR photometry consistent with $\beta_{\text{XOX}} \leq 0.5$.

3. RESULTS

As with previous work, we find very significant absorbing column densities in excess of the Galactic value for most bursts. Similarly, we also find that the mean absorption increases with redshift (Fig. 1). And while we know that the lower bound for detection of absorption increases strongly as a function of redshift, we do not reproduce the most interesting previous finding, that the upper envelope of the absorbing

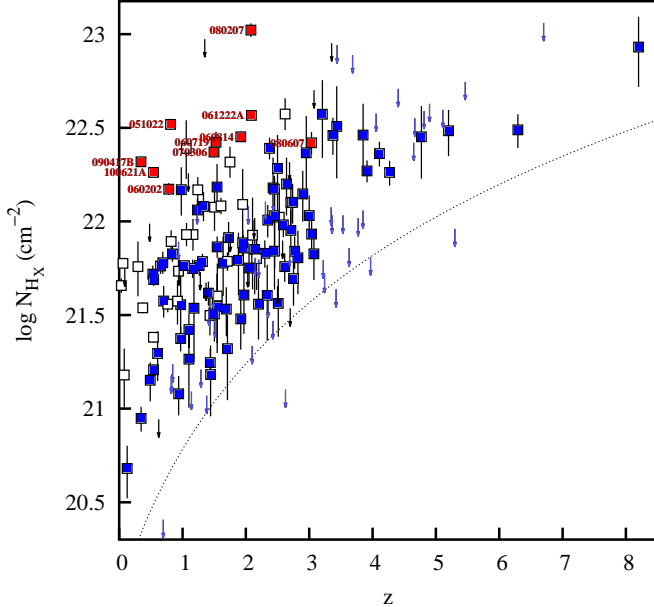


Figure 2. X-ray absorption of GRB afterglows as a function of redshift. Afterglows with extinction $A_V > 1.5$ are plotted in red, those with $A_V < 1.5$ in blue. Afterglows with unknown extinction or with 95% uncertainties spanning this boundary are plotted with open squares. The dotted line is as explained in Fig. 1. The X-ray absorptions rise systematically with redshift in the absence of the high extinction afterglows, similar to previous findings without these high extinction events. The upper bound of the absorption appears roughly constant with redshift when high extinction events are included.

column density increases with redshift (Campana et al. 2010). In the distribution shown in Figs. 1 and 2, the vast majority of objects have $\log N_{H_X} \lesssim 22.6$, with only two outliers above this value: one at $z \sim 2.2$, and the other at $z \sim 8.2$. We do not have the total absence of GRBs with $\log N_{H_X} \gtrsim 22$ at $z \lesssim 2$ found previously (Campana et al. 2010; Behar et al. 2011). The more complete, bright sample analysed in Campana et al. (2012) showed this effect as well, with a few high column density objects appearing at low redshift, allowing them to infer that the previous absence of such bursts was a selection bias.

So, why were these low redshift, high absorption GRBs missing from previous analyses? Coding the distribution by dust extinction, the answer is immediately apparent (Fig. 2); almost all of the low redshift, high absorption GRBs have high extinction ($A_V > 1.5$). These GRBs are: 051022, 060202, 060719, 060814, 061222A, 070306, 070521, 080207, 080607, and 090417B. The high restframe extinction of these objects makes it very difficult to obtain a redshift from the optical afterglow (see, for example Krühler et al. 2011, who examine eight highly-extinguished objects and find five at low redshift with high X-ray absorbing column densities). At $z = 1.5$, $A_V = 1.5$ is equivalent to a factor of more than 50 suppression of the observed V-band flux. The vast majority of these high extinction objects have redshifts obtained from the host galaxy. A good example is GRB 080207 with a redshift estimated to be $z \sim 2$ from photometric observations of the host (Hunt et al. 2011; Svensson et al. 2011). Its afterglow extinction is estimated to be $A_V \gtrsim 3.5$. This corresponds to an extinction of the flux by a factor of $\gtrsim 10^5$ in the observed V-band.

Excluding these high extinction objects, we retrieve the rising upper envelope observed by Campana et al. (2010). Indeed, it was noted by Campana et al. (2010) that dust extinction bias might explain the rising upper envelope they

observed, though the proposed explanation related to flatter extinction curves at higher redshifts is unlikely to be correct since even relatively flat extinction curves have curvature (e.g. Hirashita et al. 2008; Maiolino et al. 2004), and with such high A_V s would either render the GRB optical afterglows undetectable, or would be clearly noticeable in the broadband SED fitting (Zafar et al. 2011b). On the other hand, including all the available data, it seems clear that the upper bound of the N_{H_X} distribution is the same at low and high redshifts.

In spite of the similarity of the upper bound at high and low redshifts, it is still apparent that even in our more complete sample, the fraction of objects with a very high column density at high redshifts is still very large compared to lower redshift. This can be seen from the high ratio of detections to upper limits at high redshift, which, if the distribution was the same at all redshifts, would be significantly lower, or, equivalently, from the mean column density which still increases with redshift (Fig. 1). However our sample is not complete and almost certainly still has a strong bias against highly obscured objects. Therefore, it is not clear whether the column density distribution is the same at low and high redshifts. If it is, then a significant majority of GRBs without redshifts must be at low redshift (see, among others, Fynbo et al. 2009; Krühler et al. 2011), which means that previous estimates of the mean redshifts of GRBs were skewed to excessively high values (e.g. Jakobsson et al. 2006). Given the data so far, of course they would also have to be highly extinguished. The recent, largely complete, sample of bright GRBs analysed for their X-ray absorptions by Campana et al. (2012) still shows a mild increase in X-ray absorption with redshift, which they attribute to foreground absorbers.

4. WHAT IS THE ORIGIN OF THE X-RAY ABSORPTION IN GRB AFTERGLOWS?

The results outlined in the previous section raise more questions than they answer. The peculiarity now is no longer why there are no high absorption GRBs at low redshift, but why do high-absorption, low-extinction objects show up at high redshift, but not at lower redshifts? While we might expect a strong bias against getting redshifts for dust-obscured GRBs at high redshift, we would not expect any bias against low-extinction GRBs at low redshift.

4.1. Intrinsic curvature

We can readily exclude intrinsic curvature as an explanation for the soft X-ray downturn in the general case because the shape of the downturn does not fit typical GRB models, requiring low energy slopes different from those observed in the prompt phase (Kaneko et al. 2008) because the measured absorption is occasionally found to be constant in spite of large spectral changes, for example in GRB 100901A where we find the spectral slope changes from $\Gamma = 1.7 \pm 0.03$ to 2.2 ± 0.05 between the WT and PC data, but the excess absorptions are $4.1^{+0.4}_{-0.3} \times 10^{21} \text{ cm}^{-2}$ and $4.1 \pm 0.6 \times 10^{21} \text{ cm}^{-2}$. As an aside, intrinsic spectral curvature is observed in many blazars, but their spectra are considerably more complex than GRB afterglows and the difference in their low energy slopes is typically small, with $\Delta\beta \lesssim 0.5$ (Donato et al. 2005; Perlmutter et al. 2005). Indeed, it should be noted that intrinsic curvature has never been invoked as a general explanation, though it may play a role in the few objects at the highest redshifts (Butler & Kocevski 2007).

4.2. The warm-hot intergalactic medium

We can also exclude a smooth, highly ionised intergalactic medium, the so-called warm-hot intergalactic medium (WHIM), as the explanation for the absorption, as proposed by Behar et al. (2011). We can see very quickly that there are many GRB afterglows at $z \gtrsim 3$ with absorptions well below the apparent proposed level of the smooth WHIM (Fig. 2).

A more general argument is a structured WHIM, where it is only the average opacity above $z \sim 2$ that would tend to a detectable value while individual sightlines could have disparate values. As opposed to the smooth WHIM, individual GRB afterglows with low absorption values could be reconciled to this model. A potentially useful sample to compare to are type 1 AGN. Their spectra are known in most cases to be free of gas or dust absorption, and to show no evolution in absorbing column density as a function of redshift up to $z \sim 3$ (Mateos et al. 2010).

However, an analysis of the X-ray spectra of small samples of high-redshift AGN observed with *XMM-Newton* appear to show substantial absorbing column densities in the radio-loud, but not the radio-quiet AGN (Page et al. 2005; Yuan et al. 2006; Saez et al. 2011).

In the high-redshift, radio-loud AGN there are approximately 50% which show a downturn at low energies, and about 25% that show a noticeable upturn, suggesting that the spectra are not simple power-laws, and may be considerably more complex (Page et al. 2005). None of the seven radio-quiet objects in the Page et al. (2005) sample show a significant up- or downturn. Tavecchio et al. (2007) have suggested that the downturn observed in at least some, and possibly all (Sambruna et al. 2007), radio-loud AGN is intrinsic curvature of the low energy side of the inverse Compton emission component, and successfully modelled this in the object RBS 315. Indeed, intrinsic curvature is known in the spectra of blazars at low redshift. It mimics absorption and is present up to fairly hard energies (Perlman et al. 2005; Fossati et al. 2000). Furthermore, the apparent ‘absorption’ observed in low redshift blazars is peculiar in that no atomic absorption edges or lines are ever observed (e.g. Watson et al. 2004; Blustin et al. 2004), further strengthening the conclusion that the observed downturns are in fact due to intrinsic curvature. Therefore, finding evidence of such curvature in some higher redshift radio-loud AGN should not be a surprise. In the analysis of RBS 315, Tavecchio et al. (2007) examined two epochs of *XMM-Newton* spectroscopy taken three years apart. Fitting both datasets with an absorbed powerlaw, they found the measured absorption had increased by more than 50%. This apparent variability of the downturn argues forcibly against a WHIM origin, since the WHIM is unlikely to vary on a 3 year timescale.

4.3. High density, low-ionisation foreground absorbers

It might also be argued that the apparent increase of the X-ray absorption with redshift is related to high density (neutral or low-ionisation) intervening absorbers along the line of sight to the GRBs. And indeed, the paucity of low column density systems at high redshift is curious, though currently not highly significant statistically given that the detectability threshold at high redshift is so high. Campana et al. (2012) calculate the distribution of Ly α absorbers with redshift based on observational data and show that it is too low to explain the high absorptions observed at high redshift. They contend that the number of absorbers foreground to GRBs may be double that observed foreground to QSOs based on the numbers of high equivalent width Mg II absorbers discov-

ered (Vergani et al. 2009). Using this larger number, they find that the neutral absorbers could plausibly explain the high X-ray absorption systems found at the highest redshifts. However, they do not take into account the metallicity evolution of DLAs with redshift, but assume that the mean metallicity of the absorbers is solar. This is important since the X-ray absorption measures metals not hydrogen. Prochaska et al. (2003) demonstrate that the metallicity of intervening absorbers evolves strongly with redshift, such that the contribution from $z = 2-4$ absorbers will be 0.5–1.0 dex lower than plotted in Fig. 2 of Campana et al. (2012). This demonstrates that even by doubling the number of intervening systems, neutral absorbers along the line of sight are simply insufficient to induce the observed X-ray absorption in GRBs. Furthermore, such absorbers should be detected in the optical unless they are at very low redshift ($z \lesssim 0.3$) or have very low column density. This seems unlikely on either count, since one would have to pack a large number of absorbing systems into the redshift space $z < 0.3$ and have far fewer at $z > 0.3$, and at $z < 0.3$, we would expect to detect such absorbing systems relatively easily in emission as galaxies close to the lines of sight. In addition, the excess of Mg II absorbers is only found at very large equivalent widths; at lower equivalent widths the numbers for GRBs and QSOs are the same (Vergani et al. 2009). Thus doubling the population of low column density sources is unjustified. Another way of looking at this is to examine the relationship found by (Ménard & Chelouche 2009) between N_{HI} and Mg II equivalent width for QSO intervening Ly α systems. The mean number of high equivalent width ($W_{\lambda,0} > 1 \text{ \AA}$) Mg II absorbers found by Vergani et al. (2009) is 0.7 per redshift interval for GRBs. The typical equivalent width of these systems is a few \AA . This corresponds to a $N_{\text{HI}} \sim 1 \times 10^{20}$ for $W_{\lambda,0} = 2 \text{ \AA}$. Regardless of the redshift, this is vastly insufficient to explain the X-ray absorption. Even assuming the Mg II absorber is at $z = 0.5$, the apparent contribution to a $z = 4$ GRB is only $2 \times 10^{21} \text{ cm}^{-2}$. We would then require at least five such $z < 1$ systems for every $z = 4$ GRB, or a single system with $W_{\lambda,0} > 6 \text{ \AA}$, at $z = 0.5$ in most $z > 4$ GRBs, which is the largest equivalent width ever observed for any GRB to date. In other words, most GRBs would need to have absorption systems similar to, or larger than, GRB 991216 (Vreeswijk et al. 2006), and this is not observed (Vergani et al. 2009). In addition, we would have not to observe the corresponding galaxy at relatively low impact factor at such low redshifts. Finally, this solution does not really answer the fundamental problem of the peculiarly low dust-to-metals ratio; we would expect to observe substantial extinction if the absorbers were predominantly at moderate redshift, since DLAs appear to have a dust-to-metals ratio similar to the local group (Vladilo 1998; Ménard & Chelouche 2009).

5. THE ORIGIN OF THE APPARENT INCREASE IN X-RAY ABSORBING COLUMN DENSITY WITH REDSHIFT

We have shown that the apparent increase in X-ray absorbing column densities with redshift is mitigated when dust-extinguished bursts are included in the sample, i.e. we fill in the high-absorption, low-redshift bursts that are missing from Fig. 2 of Campana et al. (2010). We have also shown that the bursts with the highest absorbing column densities are also typically the most dust-extinguished at low-to-moderate redshift ($z \lesssim 4$). This is similar to the conclusion that there is a tight correlation between ‘dark’ GRBs and high X-ray absorption GRBs found recently (Campana et al. 2012). Further-

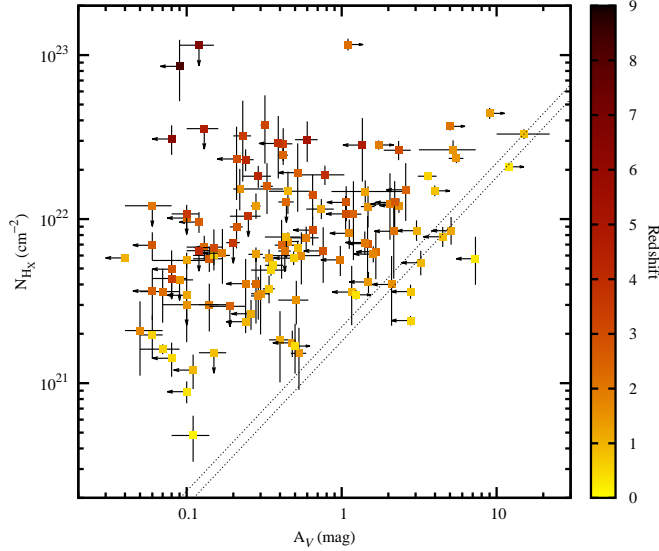


Figure 3. X-ray absorption versus extinction in GRB afterglows. Points are coded as a function of redshift. The dashed lines mark the approximate limits of the metals-to-dust ratios reported for the local group of galaxies. The absence of significant numbers of low redshift objects with high absorption and low extinction is noticeable, i.e. there is a lack of low redshift objects in the upper left part of the plot.

more, we still lack redshifts for many bursts – many of these are dark bursts and are almost certainly heavily extinguished. If most of the most highly-absorber bursts are at low redshift, i.e. are similar to the other obscured bursts we have found, they may provide the population needed to correct the apparent increase in X-ray absorption to high redshift. We therefore conclude that the increasing X-ray absorption observed so far as we go to high redshift is principally due to a dust-extinction bias. However, a complete, unbiased sample of sufficient size is required to answer this question. Campana et al. (2012) argue for a moderate remaining increase with redshift in their 90% complete sample of bright GRBs, but have insufficient statistical power to make the claim with confidence.

An increasing X-ray absorption due to a dust extinction bias is contrary to what we would naïvely expect; extinction at high redshift has a dramatic effect on the observed optical/NIR flux since we are observing the restframe far-UV where dust extinction is at its most severe. At low redshift we see that the most X-ray absorbed bursts have higher extinction. One would expect that bursts at high redshifts with large X-ray column densities would very rarely be detected. The opposite seems to be the case. This is apparent in Fig. 3, where there is a clear redshift gradient in the metals-to-dust ratio plane; in particular, no high metals-to-dust ratio objects are detected at low redshift. Such objects should be easily detected.

The simplest interpretation of this unexpected behaviour is that the fraction of metals in the dust phase is dramatically lower at $z \gtrsim 4$. However, this does not seem a very tenable hypothesis, since we know that dust does form very rapidly following formation of metals (Matsuura et al. 2011; Michałowski et al. 2010). Furthermore, there are fairly strong indications that in many environments as well as in the low-ionisation phase of the afterglow absorption, the dust-to-metals ratio is very roughly constant (de Cia 2011; Vladilo 1998; Dai & Kochanek 2009).

If a change in the metals-to-dust ratio were responsible, it would imply that the formation efficiency of dust out of avail-

able metals is at least one order of magnitude lower at $z \gtrsim 4$ than at lower redshifts. But as indicated above, we do not find this a likely explanation. There must be other explanations for this apparent change, and we note that the mean metallicity decreases strongly with redshift (Prochaska et al. 2003) and this change may reflect the more pristine environments found earlier in the age of the universe. It will be difficult to solve this mystery for certain until we have a clear idea of what causes the X-ray absorption and precisely where it occurs.

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